Cost-based dimensioning of Battery Energy Storage and energy management system for Frequency Containment Reserves provision

Julien Jomaux[1], Arnaud Latiers[2], Emmanuel De Jaeger[1]

[1]Center for Research in Energy and Mechatronics (CEREM), [2]Center for Operations Research and Econometrics (CORE)

Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium

{julien.jomaux, arnaud.latiers, emmanuel.dejaeger}@uclouvain.be

***Abstract*—Frequency Containment reserves (FCR), previously called primary reserves, are an important feature insuring safe and reliable operations of the Continental Europe grid. Due to their strong technical requirements, gas and hydro power plants are the almost exclusive provider of FCR. Since gas power plants are becoming less profitable in Europe, a lot of efforts are deployed into FCR diversification. This paper assesses the potential for battery energy storage systems (BESS) to deliver FCR combined with a slow-moving thermal power plant and other emergency solutions such as load shedding and dissipating resistances. A proportional-integral energy management control loop is used whose parameters are tuned by an economic evaluation. We show that economic opportunity already exists today. Some limitations are discussed due to simplifying assumptions. The best solution consists of a 1MW/1.4MWh battery and a 0.09MW power plant per MW of provided FCR reducing by 90% the reservation on power plants.**

***Index Terms*—Battery Energy Storage, Energy management, Frequency Containment Reserve, Power systems.**

I. INTRODUCTION

Among the particular features that may differ between two separated power systems, load-frequency control and reserves are probably the most specific. The Continental Europe (CE) grid has three main categories of reserves, namely frequency containment reserves (FCR), frequency restoration reserves and replacement reserves. FCR have the fastest response and generally correspond to the generation droop control. In various countries, as Germany, the Netherlands and Belgium, a market has been set in place to secure sufficient FCR volumes. Alternatively, other power grids such as those in the US have been recently modifying other reserve layers (e.g., regulation with pay-as-performance or Reg-D signal) in order to increase the response speed of their operating reserves.

In Europe, technical requirements of FCR limit the potential candidate providers to fast power generators (e.g., open-cycle gas power plants) and hydro power plants. Due to the decreasing profitability of gas power plants, some countries, such as Belgium, are experiencing FCR price increases[1]. This price risk is encouraging the evaluation of original solutions for providing these reserves. This article presents one of them: the use of battery energy storage system (BESS) in combination with a slow-reacting power plant.

Battery energy storage is currently undergoing a cost decrease [2]. Therefore, applications are attracting System Operators' attention. FCR having high power to energy ratio, they turn consequently interesting for such form of energy storage. Yet, BESS will experience energy losses and cannot provide FCR alone for infinite time periods. Its energy level has to be restored either directly (e.g., energy level restoration from a power plant) or indirectly by adapting the FCR's requirements (e.g., asymmetric FCR).

The present article explores a flexible portfolio combining a battery energy storage system with a generation unit (ideally situated on the same site) for energy management purpose. In addition, two emergency solutions, demand reduction and resistances, are considered. The power plant provides by far the biggest share of the energy restoration while the two other elements are required only for extreme cases. This paper provides a first technical and economic assessment of the proposed system in order to (1) estimate its viability and (2) assess the optimal sizing of its elements.

II. ENERGY CONTENT OF FCR

A. Percentage use of FCR capacity over time

FCR participating units are in theory required to provide the reserved power capacity at any moment and continuously during two consecutive quarters of hour. In practice, the actual average use of the reserved power is much lower as Fig. 1 shows. Indeed, CE grid experiences very high frequency[2] quality leading to very high power to energy ratio for FCR that could potentially be interesting for BESS.

---

[1] FCR prices have fluctuated from 34.74€/MWh in February 2014 to 152.73€/MWh in April 2014 [1].

[2] Courtesy of Elia System Operator - 2013 frequency measurements (10s). Simulations of this paper are based on these measurements.

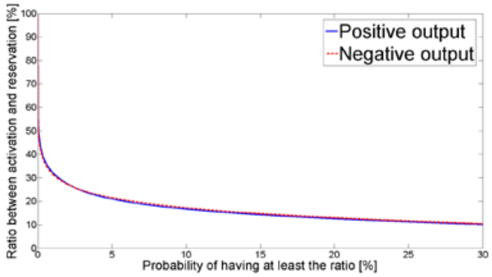

Figure 1. FCR activation based on 2013 frequency.

The average use of reserved power on larger time periods is even lower, and so is the average energy content of FCR's reaction. In practice, batteries could therefore provide the fast moving part of FCR reaction, while a small energy correction should be compensated by power generation. Fig. 2 presents the FCR use ratio for different moving averages (positive reaction only). In this case, FCR use stays below 10% of the reserved power during respectively 70%, 80% and 90% of the time for 10s, 5 minutes and 30 minutes averaging periods.

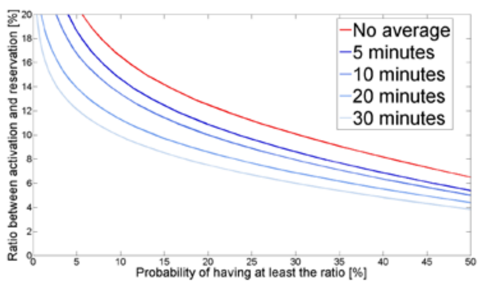

Figure 2: Average FCR use curves for different averaging periods.

B. *Energy requirements*

Due to system frequency's lack of predictability, FCR activations are unforeseeable. Furthermore, FCR's net delivered energy, when provided by storage even for limited period of times, may represent a couple of hours of continuous (dis)charging. Fig. 3 shows energy requirements during three different periods of two weeks. BESS providing such energy while counteracting its natural losses would require very large energy capacity, and would turn unprofitable if used alone.

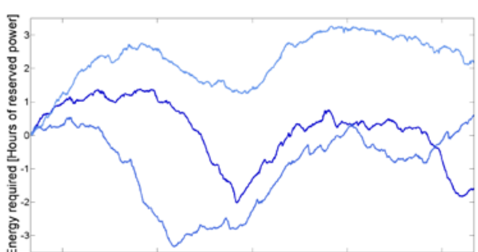

Figure 3. Examples of energy requirement (two weeks).

C. *Interest of combination storage – Power plant*

FCR are most of the time provided by gas or hydro power plants by reserving part of the plant's power capacity. This unused power represents a non-negligible opportunity cost leading to suboptimal dispatch. On the other hand, storage cannot efficiently and safely provide FCR without interruption since the energy requirement can be significant. In the proposed solution, a battery is used as a buffer between fast moving FCR reaction and average (slow moving) FCR use. The power plant capacity required for energy management purpose is much lower than the provided FCR capacity. As the results show, the optimal solution leads to a power plant capacity of around 10% of the provided FCR capacity. Since FCR revenues comes from capacity payments a 1MW power plant becomes equivalent to a 10MW one when adding a storage buffer.

III. Details of the Proposed solution

A. *The flexibility portfolio's elements*

The proposed solution is composed of three different elements: (a) battery energy storage, (b) power plant and (c) emergency solutions. The latter ensures that the system is always able to cope with strong FCR technical requirements even in extreme and unlikely cases[3]. The emergency solutions are twofold: resistances for negative power reaction and demand-side management in the form of load shedding for positive power reaction. Emergency solutions use is restricted to extreme cases. Therefore, solutions having low fixed costs with high activation costs were preferred.

B. *System's core principle: linear filtering*

This section presents the core theoretical principle of the proposed system. In normal operations (i.e., no need for emergency elements, assuming instantaneous lossless storage reaction) the solution is simplified to the system on fig. 4. P_{FCR}, P_p and P_s denote respectively the FCR power, the power plant power and the battery storage power. All *set* superscripts are referring to set points. G_s represents a constant proportional gain.

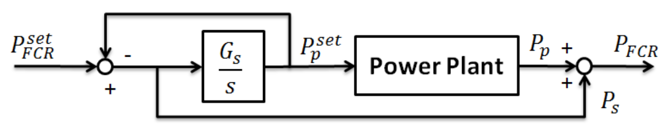

Figure 4. Representation of the proposed system. A low-pass filter is inserted between the FCR signal and the power plant set-point.

In the Laplace domain ($\mathcal{L}\{\cdot\}$, variable s), the transfer function between the Laplace transforms of P_p^{set} and P_{FCR}^{set} is given in (1).

$$\mathcal{L}\{P_p^{set}\} = \frac{1}{1+\frac{s}{G_s}}\mathcal{L}\{P_{FCR}^{set}\} \tag{1}$$

The system acts as a low-pass filter on the FCR set point signal. The power plant set point P_p^{set} consequently varies less rapidly and is adapted to slow power plants. This signal subtracted from the reference signal P_{FCR}^{set} is the battery storage set point P_s^{set} as shown in (2).

$$\mathcal{L}\{P_s^{set}\} = \frac{\frac{s}{G_s}}{1+\frac{s}{G_s}}\mathcal{L}\{P_{FCR}^{set}\} \tag{2}$$

[3] e.g., sustained negative system frequency deviations. In such case, the storage gets discharged and the power plant cannot deliver the FCR power.

The factor G_s defines the cutoff frequency of the filter and should be adapted to the power plant's ramping rate limits ensuring power plant linear reaction. The system output would match the FCR set-point as required $P_{FCR}^{set} = P_{FCR}$.

C. Comparison with other solutions

Several works have studied the alternatives for providing FCR. Storage has been proposed as a potential provider [3]-[4] but generally without explicitly considering the recovering energy provider. Exchanges of FCR reserves through HVDC lines have also been proposed [5]. For the CE grid, this exchange can be realized with the Nordic grid or with the United Kingdom. Variable renewable power (e.g., wind turbines) has been considered in [6]-[7] though the reserved power capacity leads to an inefficient use of such low marginal cost resource.

The contribution of this paper lays in the assessment of FCR provision from a portfolio. In particular, simulations over long time periods are rarely performed. Moreover, this solution can be directly implemented on site by installing the storage facility next to the power plant.

IV. Complete System Modeling

A. Technical model

1) Energy management control loop

The full system control loop is presented on Fig. 5. The frequency is measured on site and determines the FCR power set-point (in blue). This set-point, from which the sum of all energy compensation components (power plant, etc.) are subtracted, is sent to the battery storage. To close the loop, the battery state of charge (E_s) is taken as input signal for controlling the power plant and the emergency elements (demand reduction and resistances) contributions.

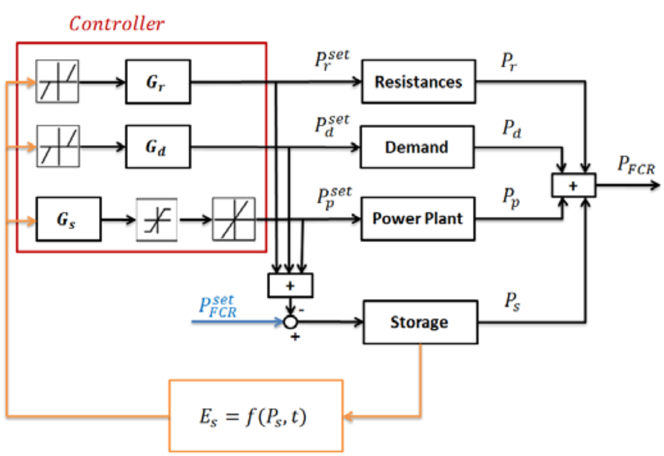

Figure 5. Control loop of the FCR portfolio system.

2) Battery Storage Model

The battery storage state of charge evolution E_s considers three parameters: the charging efficiency (η_c), the discharging efficiency (η_d) and the self-discharging losses (P_{sd}) as shown in (3). Battery's response dynamics are modeled by a rate limiter as well as an absolute saturation limit on power deviations P_s.

$$E_s(t_k) = \begin{cases} E_s(t_{k-1}) - P_s\eta_c - P_{sd}\Delta t & if\ P_s < 0 \\ E_s(t_{k-1}) - \dfrac{P_s}{\eta_d} - P_{sd}\Delta t & if\ P_s > 0 \end{cases} \quad (3)$$

3) Power plant Model

A rate limiter represents the power plant ramping constraints. This rate limiter is set to a relatively low value in comparison with the ramping required to provide FCR. A saturation block is also used to limit the maximum available power.

4) Resistances

Resistances are used in case battery's state $E_s(t_k)$ of charge go over a certain threshold value $L_r E_s$. The resistances dynamics are neglected (no ramp limits) and have infinite power capacity.

5) Demand reduction

Demand reduction is modeled as discrete power blocks. Demand will be reduced in case battery's state of charge goes below a threshold $L_d E_s$. Demand reduction activation consists in a constant power P_d decrease lasting for a time t_d disregarding the new state of charge. There is no activation delay (demand decreases immediately).

B. Economic considerations

1) Storage costs

Three parts are accounted for as storage costs: an installation cost $C_{s,c}$, a replacement cost $C_{s,r}$ and an annual maintenance cost $C_{s,m}$. The storage installation cost is determined by the installed storage size (energy E_{si} in MWh) and power capacity P_{si} in MW as in (4).

$$C_{s,c} = P_{si}\pi_p + E_{si}\,\pi_e \quad (4)$$

with π_p,π_e respectively the cost per installed MW and MWh.

Battery storage systems have limited lifetime. The number of charging/discharging cycles they are able to deliver is limited. Therefore, replacement cost $C_{s,r}$ has to be taken into account if the number of cycles goes beyond a limit n_s. As the simulation spans on one year, we extrapolate the number of cycles at the end of the simulation n_1 on the total number of years n_y considered in the project. The total number of replacement n_r and the different replacement years take into account the cycle limit n_s. From there, we determine the replacement costs over the whole period as in (5) and (6).

$$n_r = \left\lfloor \frac{n_y n_1}{n_s} \right\rfloor \quad (5)$$

Where $\lfloor x \rfloor$ returns the largest integer $\leq x$ (floor function).

$$\forall i \in [1, n_y] : C_{s,r}(i) = \begin{cases} 0\ if\ \ no\ replacement\ in\ year\ i \\ C_{s,c}\ if\ replacement\ in\ year\ i \end{cases} \quad (6)$$

Finally, the annual operation and maintenance cost ($C_{o,m}$) is proportional (with factor K_m) to the installation cost.

2) Power plant costs

Two components are taken into account for the power plant. The first is a loss-of-opportunity cost ($C_{pp,o}$) that emerges from non-using the full power plant capacity. It is modeled as a percentage K_p of the average FCR price π_{FCR}[4]. This is a simplified view of reality. For instance, must-run costs of gas power plants could influence this cost and would need to be compared to the hour-to-hour bulk energy price.

The second component is a generation cost. The power plant will have to generate a net amount of energy due mainly to the inherent storage losses. This cost ($C_{pp,e}$) is an annual cost and is determined by multiplying the net generated energy E_{PP} with the electricity price (π_{el}) . E_{PP} is expressed in (7) and includes the energy required for FCR (E_{FCR}).

$$E_{PP} = \int \left[\frac{1-\eta_d}{\eta_d} P_d(t) - (1-\eta_c)P_c(t) + P_{s,sd}\right] dt + E_{FCR} \quad (7)$$

Where $P_d = \begin{matrix} P_s & if & P_s > 0 \\ 0 & if & P_s \leq 0 \end{matrix}$ and $P_c = P_s - P_d$

3) Demand Reduction costs

We consider that demand reductions are supposed not to require any investment. Indeed, as final dimensioning will minimize their use, it is justified to exploit existing demand response programs (e.g., under-frequency load shedding). Considering operational costs, both a reservation cost ($C_{d,r}$) and an activation cost ($C_{d,a}$) are considered. The demand reduction total cost (C_d) is the sum of both elements. The reservation cost is proportional (with factor K_{dr}) to the maximal power required during the different activations (P_d). The activation cost is proportional (with factor K_a) to the number of activations n_d.

4) Resistances costs

Symmetrically to demand reductions, the resistances are merely used, during extreme cases. Such resistances are considered to be maintenance free as they are relatively simple. Moreover, their cost is proportional (with factor K_r) to the maximal power required during all the activations (P_r). Consequently, if no activation has been made, no resistance is actually needed and the cost drops to zero.

5) Total Cost function and comparison to FCR revenues

In order to compare the costs of the proposed solution with the present FCR prices, we report the costs on n_y. Three categories of costs are calculated. The initial investments are the installation of the storage facility as well as the installation of the resistances. Secondly, the storage replacement is a capital cost that occurs for specified years. Finally, the operational costs are the opportunity cost of the power plant, the maintenance cost, the cost of generation, the reservation and the activation of DSM. All the costs are actualized by taking into account a discount rate (i_d) and the total actualized cost (C_T) is calculated in (8).

$$C_T = C_{s,c} + C_r + \sum_{t=1}^{n_y} \frac{C_{s,m} + C_{pp,o} + C_{pp,e} + C_d}{(1+i_d)^t} + \sum_{t=1}^{n_y} \frac{C_{s,r}(i)}{(1+i_d)^t} \quad (8)$$

The total cost has to be compared with the FCR revenue in order to assess the economic profitability.

[4] The justification is that up to now, FCR price is mainly determined by the power margin required to gas power plants.

C. Limitations

The proposed model is relatively simple and therefore carries some limitations. Firstly, optimal storage management is not considered and more detailed storage modeling such as maximal number of cycles and dependence on the cycle's depth of discharge are left aside. Secondly, since this paper does not aim to be an extensive financial analysis, economic modeling takes no considerations on weighted-average capital costs or exact evaluation of the return on investment.

V. TEST CASE

A. Simulation Parameters

The technical and the economic parameters used for the test case are presented in respectively tables I and II. Numerous other test cases could have been possible by taking other parameters. This papers aims to present a realistic scenario and to assess the value of the proposed model. Realistic but conservative choices have been made: (a) the storage is a central battery system (lithium titanate) with values based on [8]-[9], (b) the simulation is for 10 MW of FCR provision representing 0.33% of the total European need for FCR and (c) only two simulation variables are considered: the reserved power plant capacity and the storage energy content since they have the biggest impacts on results. This test case aims at finding the best values for these variables.

TABLE I. TECHNICAL PARAMETERS

Parameter	Variable	Value	Unit
FCR provision	P_{FCR}	10	MW
Droop controller	K	-50	MW/Hz
Storage charge efficiency	η_c	90	%
Storage discharge efficiency	η_d	90	%
Storage ramping	R_s	10/30	MW/s
Storage power capacity	P_{si}	10	MW
Storage cycle limits	n_s	3000	Cycles
Storage self-discharge	P_{sd}	0.1	MW
Storage energy installed	E_{si}	[10;20]	MWh
Capacity reserved	P_{pi}	[0.1;1.2]	MW
Power Plant Ramping	R_p	1/60	MW/s
Resistances : activation	L_r	80	$\%\ of\ E_s$
Demand reduction: activation	L_d	20	$\%\ of\ E_s$
Demand reduction : time	t_d	300	s
Simulation time step	Δt	10	s

TABLE II. ECONOMIC PARAMETERS

Parameter	Variable	Value	Unit
Discount Rate	i_d	4	%
Number of year	n_y	15	Years
Storage Price – Power	π_p	700	k€/MW
Storage Price - Energy	π_e	400	k€/MWh
Storage Maintenance	K_m	10	% / year
Ratio reserved capacity – FCR	K_p	120	%
Price FCR	π_{FCR}	35	€/MW.h
Electricity price	π_{el}	50	€/MWh
Demand reduction – reservation	K_{dr}	30000	€/MW.h
Demand reduction - activation	K_a	400	€/activation
Resistances	K_r	10000	€/MW

B. Results

Fig. 6 presents the total cost of providing FCR during 15 years for various pairs of parameters $[E_{si}, P_{pi}]$. The total cost is minimal when: (a) the energy storage is sufficient to avoid replacement costs, (b) use of demand reduction and resistances is avoided.

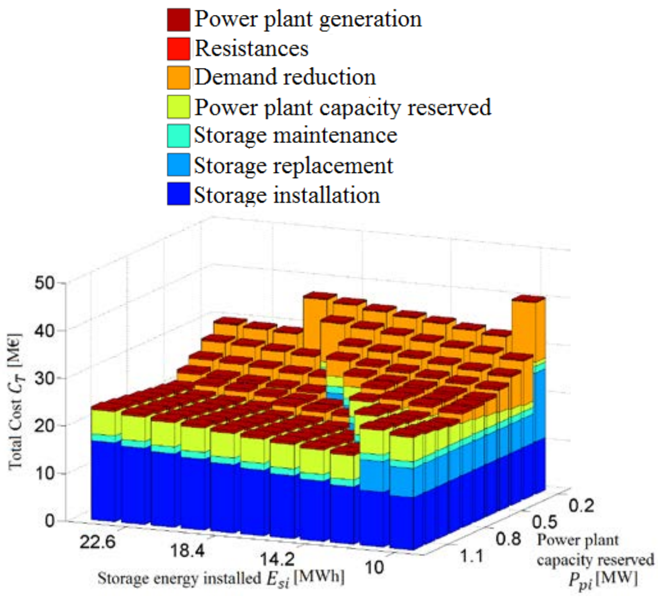

Figure 6: Results of the simulation. Cost of 15years provision of 10 MW FCR.

Minimal cost arises for $[E_{si}, P_{pi}] = [14.2MWh, 0.9MW]$. With these values, the total cost is 18.58M€. It has to be compared with the revenues generated from FCR. The discounted revenues over the 15 years are estimated to be 35.55M€. The system is thus without hesitation cost-efficient. Cost shares for the best solution are shown in Fig. 7.

These results are promising. They offer an efficient alternative to gas and hydro power plants for FCR provision. Results suggest that a reduction of 90% to the current required reserves on gas power plants is achievable.

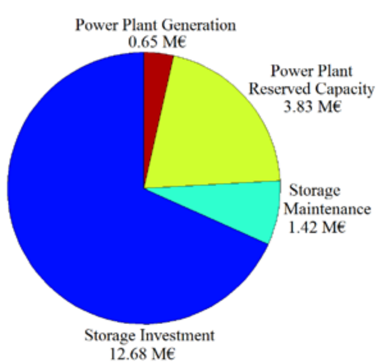

Figure 7. Cost shares of the best 10MW FCR solution.

VI. CONCLUSION

FCR are an important element for the safe operation of the CE grid. Due to external elements, such as the low coal prices in Europe and the increasing penetration of renewables, FCR price is likely to soar. Original solutions for providing these reserves should thus be envisaged. This article presents the combination of power storage with a power plant and eventually emergency solutions, to provide FCR. A technico-economic modeling has been performed in order to assess the potentiality of the proposed system.

It has been shown that, at current technology costs and FCR prices, the proposed system has already an economical interest. On a period of 15 years, it provides FCR at almost half the actual FCR price of some regions such as Belgium. Moreover, it eases the introduction of new participants into the FCR markets: a) relatively slower power plants such as coal power plants and b) large scale power storage. This system represents thus an original solution for countries with shortfall on gas power plants as it is the case in some countries in Europe.

Further investigations should be carried out to validate and even improve the proposed system. Firstly, an assessment of the most relevant and economical technologies should be made. Indeed, other technologies with different technical and economical values can be better that what it is proposed in this paper. Secondly, a more detailed modeling of the system is required for validation. Finally, an extensive financial assessment should be established for evaluating the real potential of the proposed system.

REFERENCES

[1] Elia System Operator, «Ancillary Services: Volumes and Prices,» [online]. http://www.elia.be/en/suppliers/purchasing-categories/energy-purchases/Ancillary-Services-Volumes-Prices. [11 September 2014]

[2] Rocky Mountain Institute, "The Economics of grid defection," www.rmi.org, Feb. 2014.

[3] T. Borsche, A. Ulbig, M. Koller, and G. Andersson, "Power and energy capacity requirements of storages providing frequency control reserves," *IEEE Power and Energy Society General Meeting (PES)*, pp. 1-5, Jul. 2013.

[4] A. Oudalov, D. Chartouni, and C. Ohler, "Optimizing a Battery Energy Storage System for Primary Frequency Control," *IEEE Transactions on Power Systems*, Vol. 22, 3, pp. 1259-1266, Jul. 2007.

[5] J. Dai, Y. Phulpin, A. Sarlette, and D. Ernst, "Coordinated primary frequency control among non-synchronous systems connected by a multi-terminal high-voltage direct current grid," *IET Generation, Transmission & Generation*, vol. 6, n°12, pp. 99-108, Jan. 2012.

[6] I. Erlich, and M. Wilch, "Primary frequency control by wind turbines," *IEEE Power and Energy Society General Meeting*, pp. 1-8, Jul 2010.

[7] J. Morren, S.W.H de Haan, and J.A. Ferreira, "Primary power/frequency control with wind turbines and fuel cells," *IEEE Power and Energy Society General Meeting*, pp. 1-8, Jun. 2006

[8] A. Burke, M. Miller, The UC Davis Emerging Lithium Battery Test Project, 54, (June 2009) 24. UC Davis, Institute for Transportation Studies.

[9] C. Budischak, D. Sewell, H. Thomson, L. Mach, D. E. Veron, and W. Kempton, "Cost-minimized combinations of wind power, solar power and electromechanical storage, powering the grid up to 99.9% of the time," *Journal of Power Sources 225*, n°225, pp. 60-74, 2013.